NIST in Space: Better Remote Sensors for Better Science

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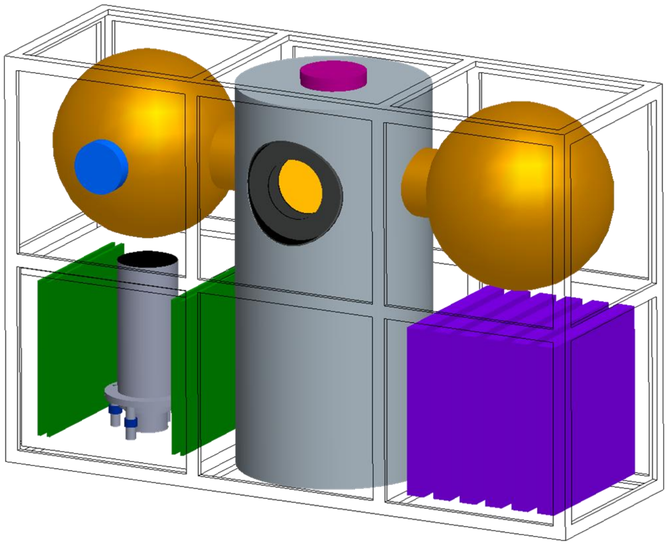

Climate Class Remote Sensor Measurement Accuracy Across the Solar Band

NASA Innovative Advanced Concepts
Spring Symposium
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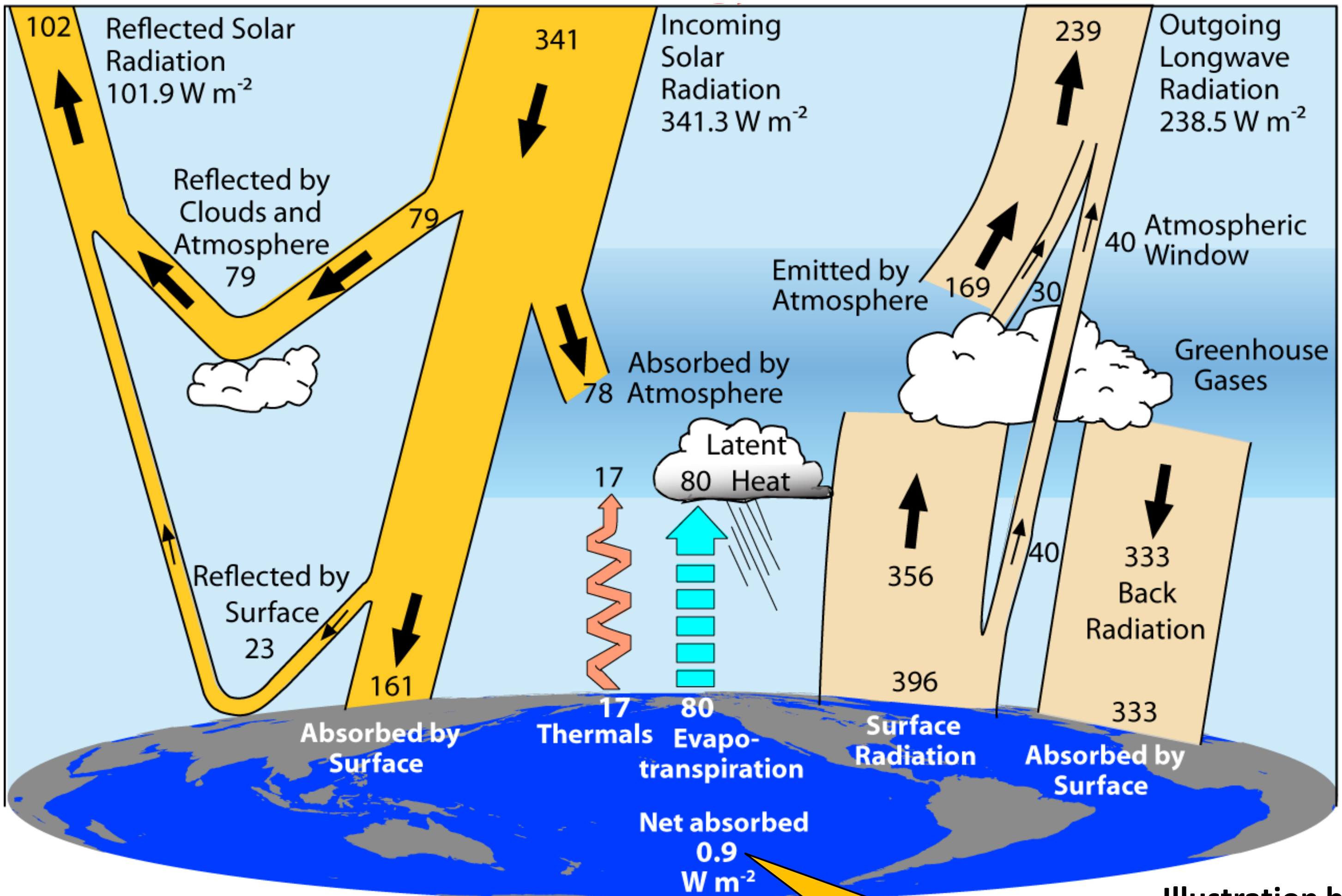
Objectives

- ✓ Develop breakthrough UV/VIS/NIR remote sensor calibration concept to enable climate trending & improved earth science for many NASA missions
- ✓ Improve measurement accuracy over current space technology by one order-of-magnitude
- ✓ International Standard (SI) traceable radiance measurements
- ✓ Spectrally resolved over full solar range

Why This Is Important?

- Most comprehensive insight into earth, sun, & deep space energy balance is provided by observations from space
- Understanding earth energy balance is key to understanding forces that drive climate change
- Ultraviolet to far-infrared wavelengths are all important (0.2 um - 100 um)
- Climate change driven by only ~0.3% change in this energy balance
- Observation in solar band are the most challenging and without current technology suited to the task

Radiation Exchange Between Earth, Sun & Space Is Enormous But Imbalance Driving Climate Change Is Small

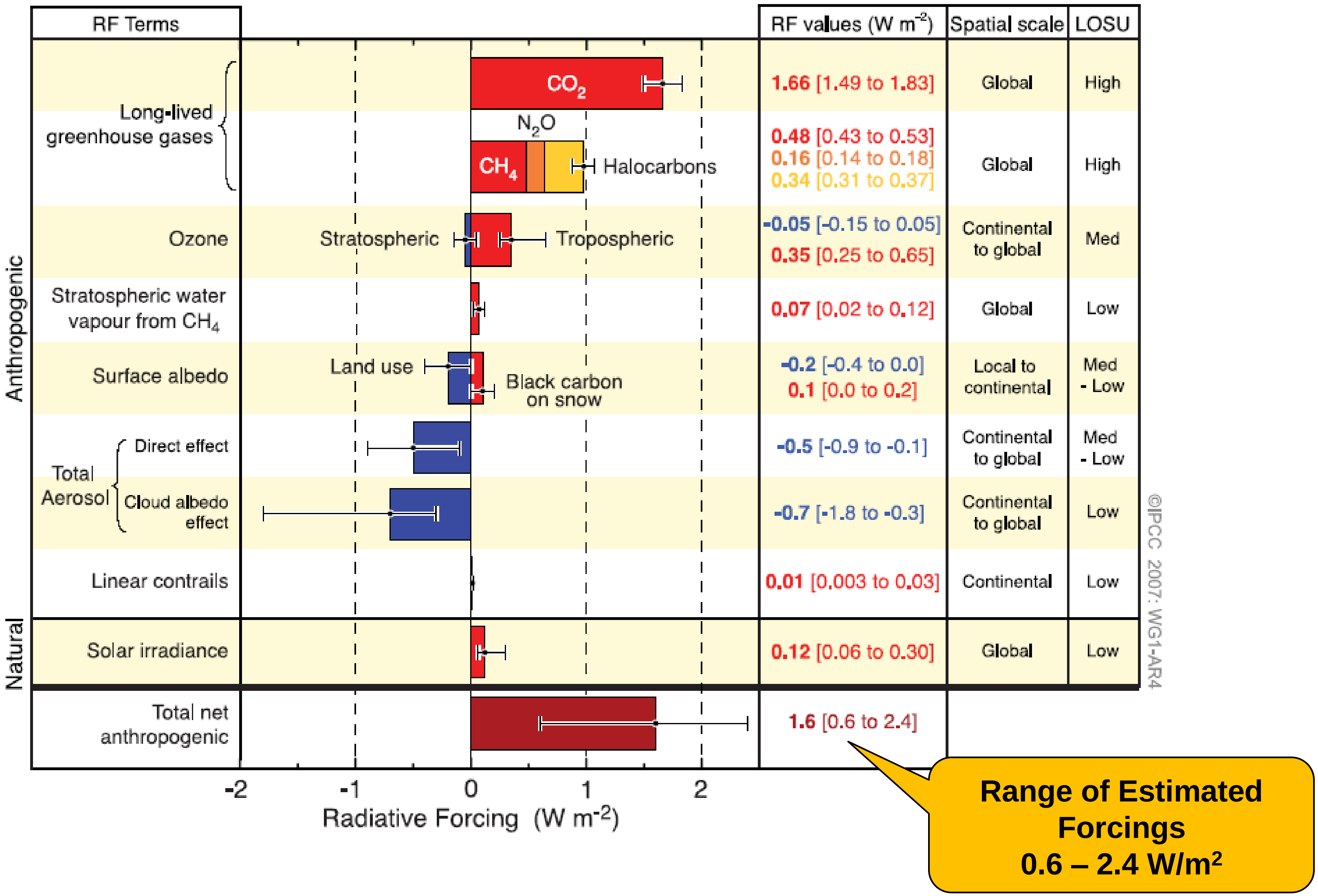


Net Imbalance 0.9 W/m²

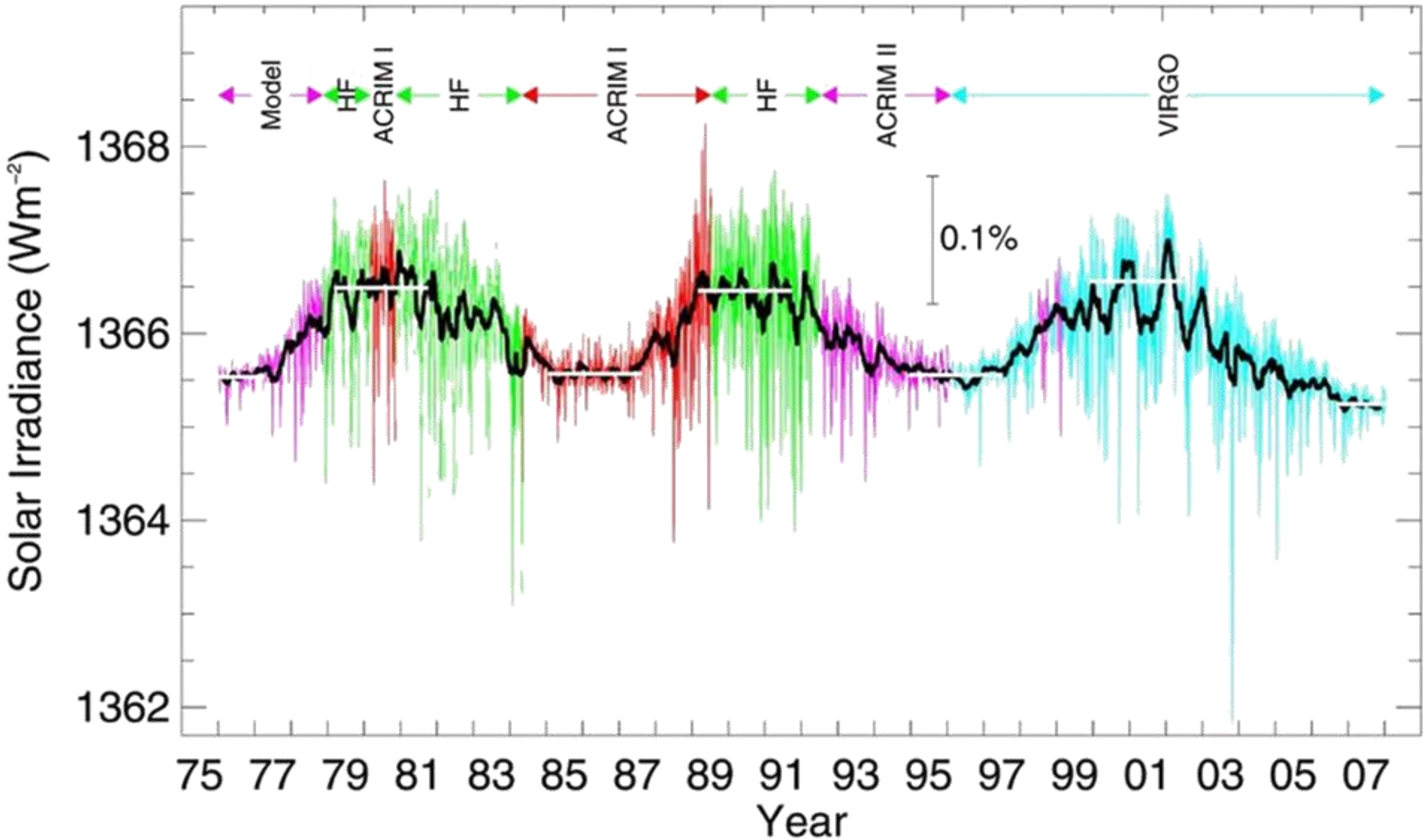
Illustration by Trenberth 2010

Note: Numbers represent spatial & temporal average over entire globe

Climate Models Have Large Uncertainty in Radiative Forcing Estimates…….Need Satellites to Resolve



Solar Irradiance Reported for Last Three Solar Cycles
(from Fall 2008 AGU Meeting)



However, Satellite Sensors Differ Considerably in Their Reported Observations of Total Solar Irradiance

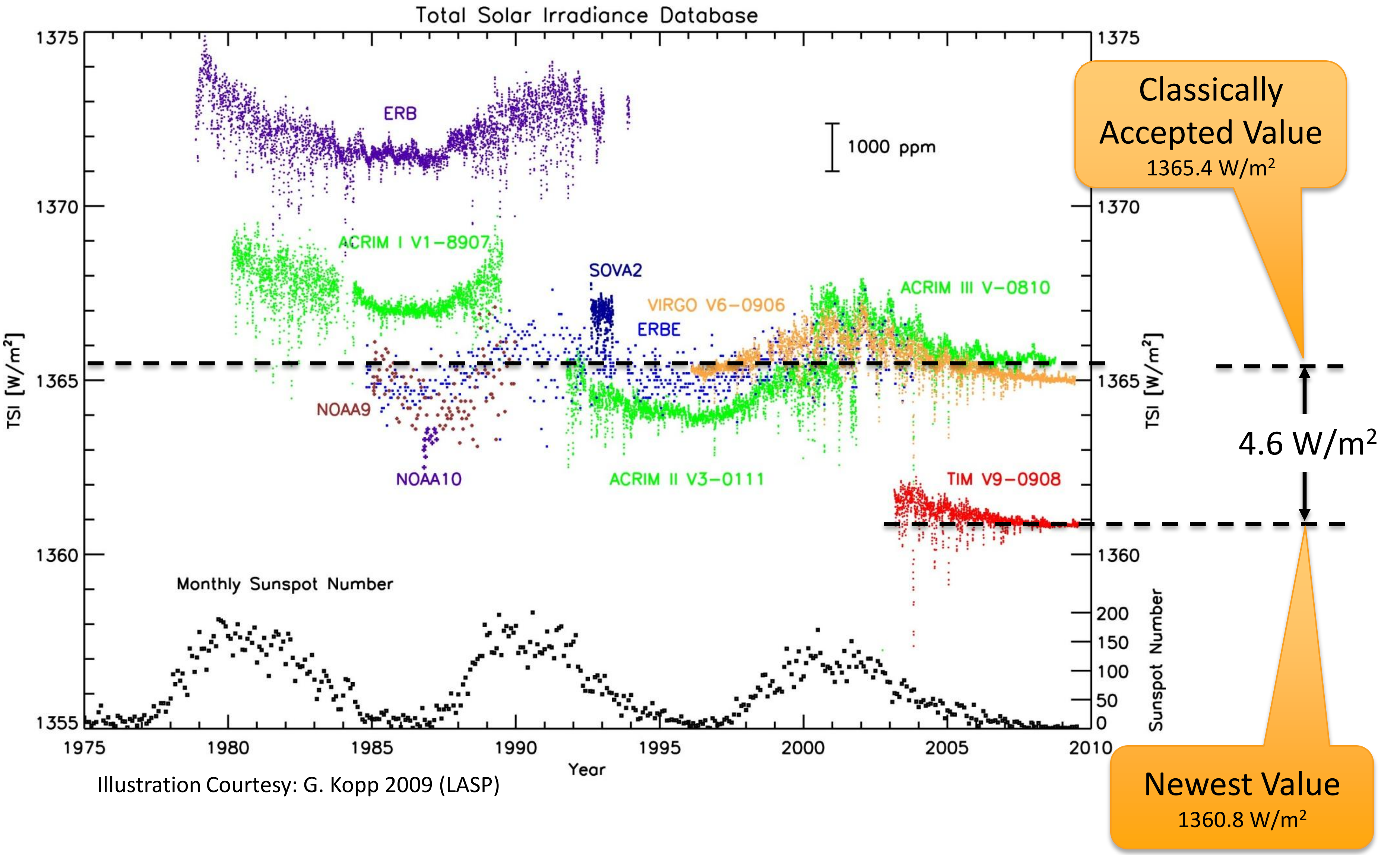
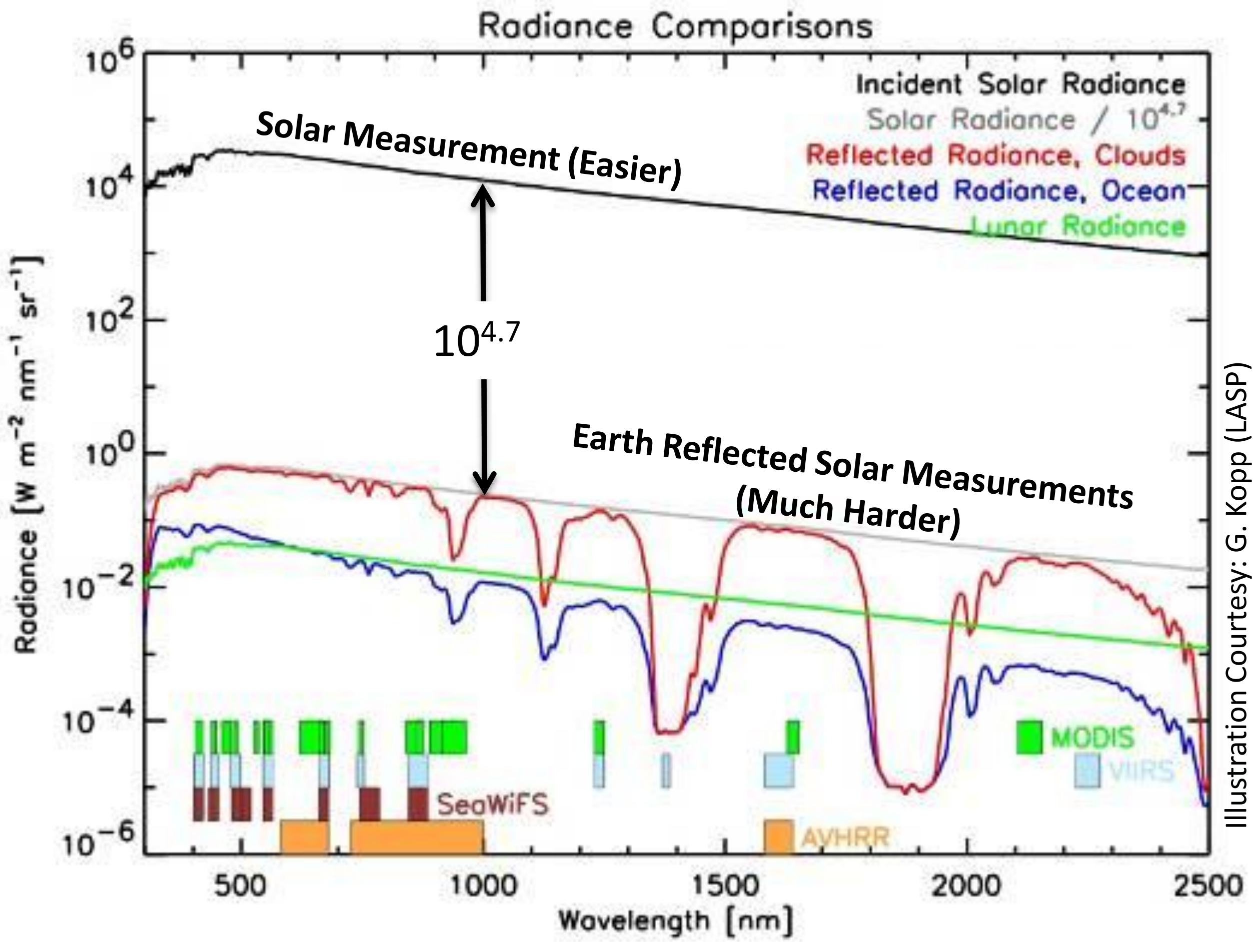


Illustration Courtesy: G. Kopp 2009 (LASP)

Solar Radiance & Earth Reflected Radiance Differ Enormously & Measuring this Accurately Is Difficult

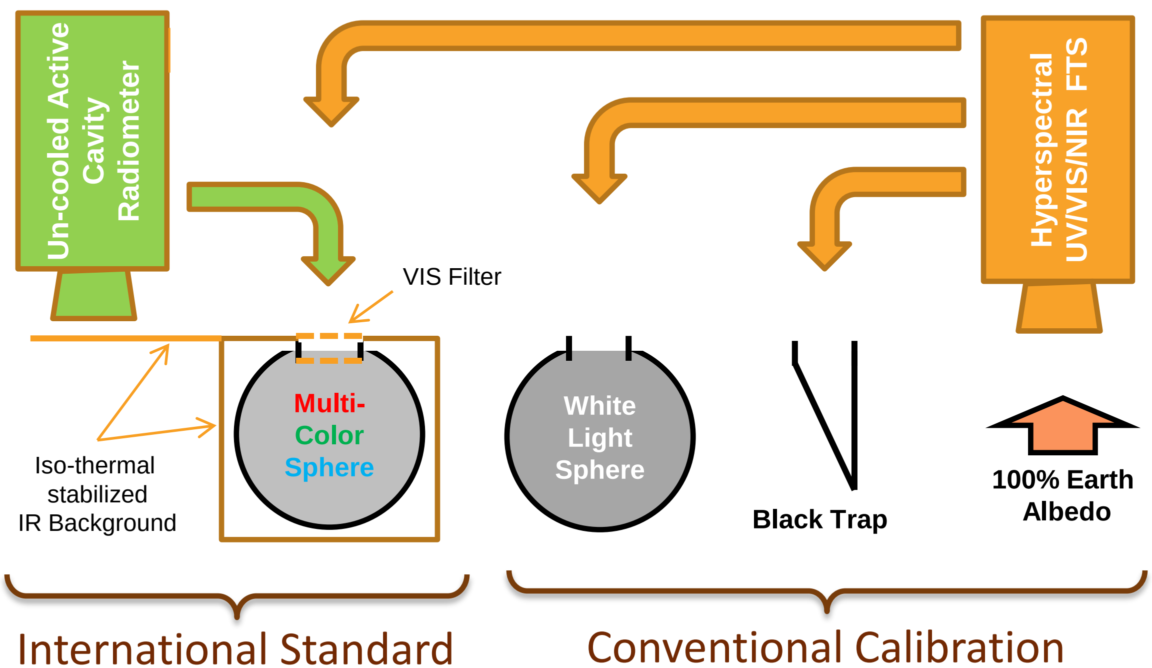


How can accurate measurements be made from space to trend climate forcings?

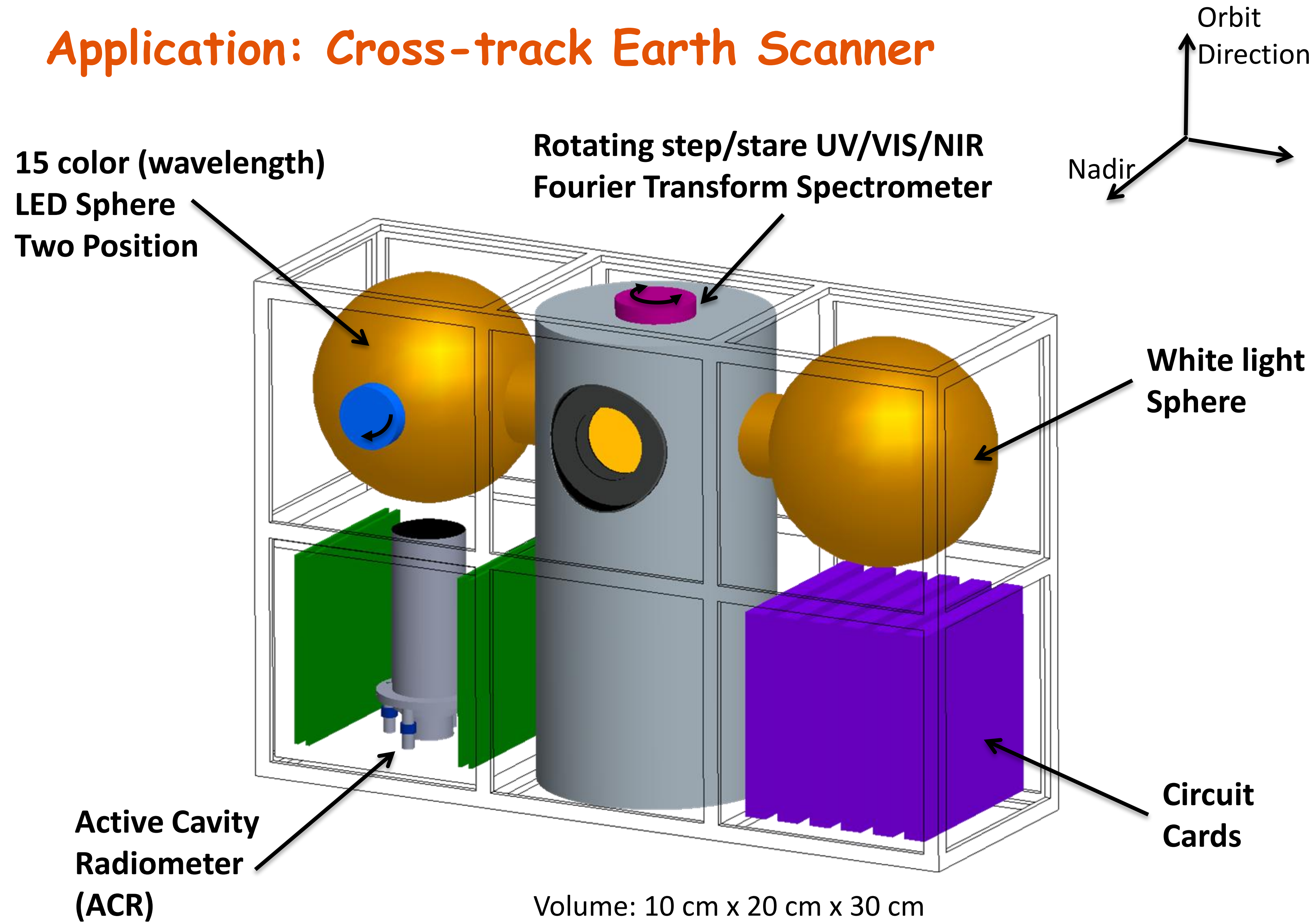
NIST in Space: Spectrally Resolved Earth Reflected Solar Radiance Measurements Tied Directly to an International Standard (SI) …………with <0.1% Uncertainty

NIST in Space Concept

1) Un-cooled broadband Active Cavity Radiometer (ACR)
2) Multicolor LED driven integrating sphere
3) White light integrating sphere
4) Black target
5) Hyperspectral UV/VIS/NIR Fourier Transform Spectrometer



Application: Cross-track Earth Scanner



Volume: 10 cm x 20 cm x 30 cm

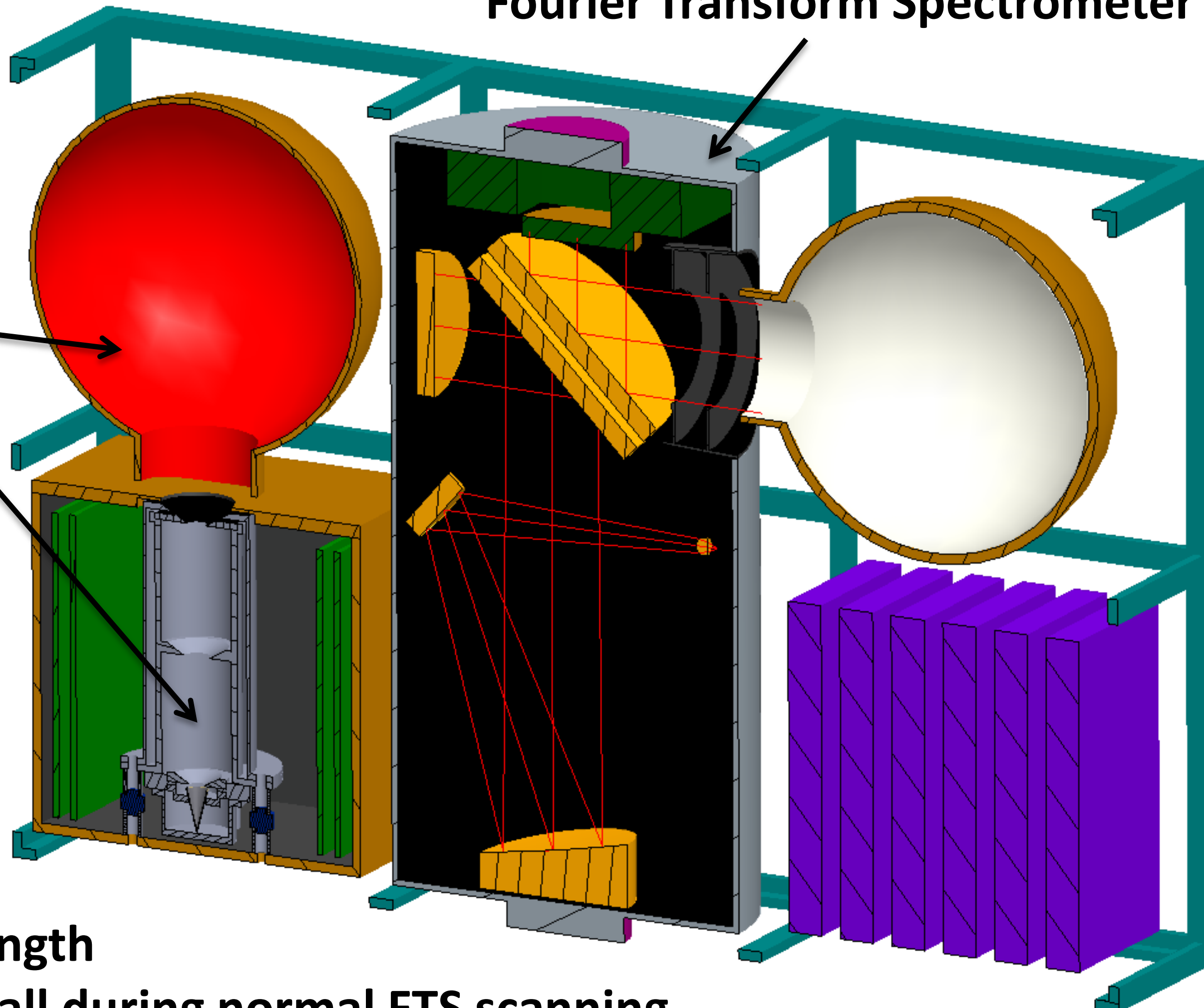
FTS Scans Earth & White Light Sphere While LED Sphere Undergoes NIST Traceable Calibration by ACR

Fourier Transform Spectrometer (FTS)

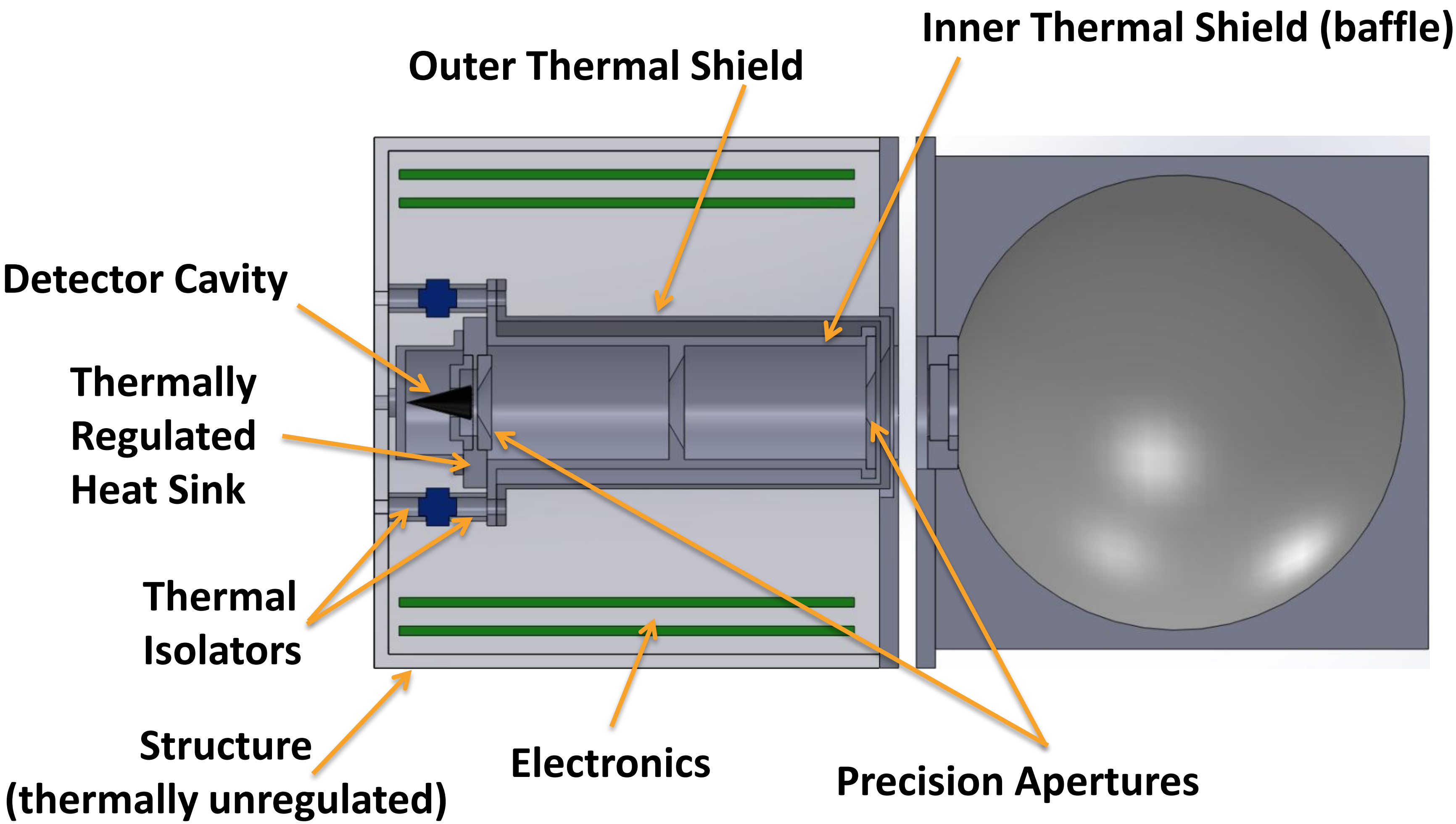
6 minutes to calibrate each LED radiance

Process repeats for 15 LED wavelengths (265 nm – 3000 nm)

Monitor detectors within sphere remember each wavelength calibration for quick recall during normal FTS scanning

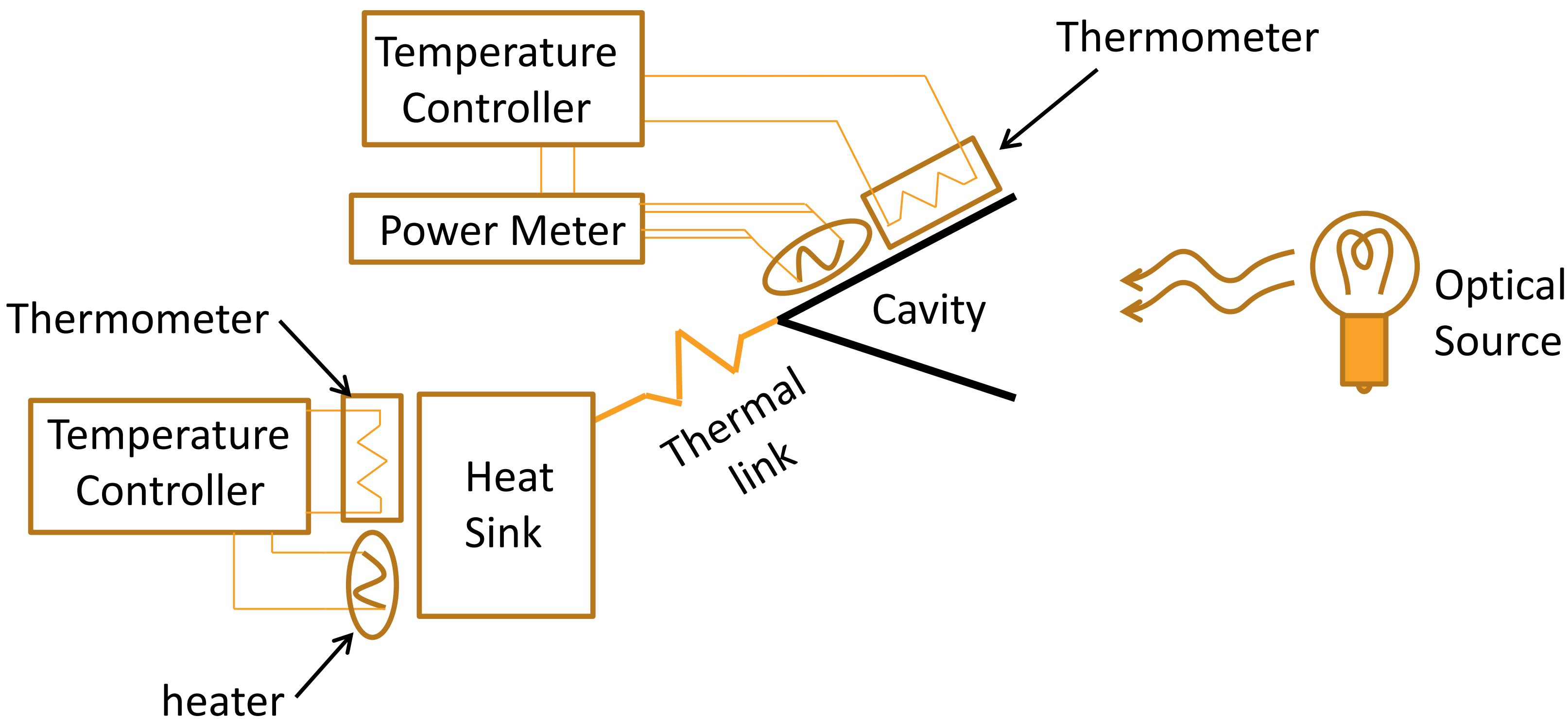


We Have Developed a Broadband ACR Having 10 nanoWatt NIST Traceable Optical Power Measurement Accuracy Operating at Room Temperature



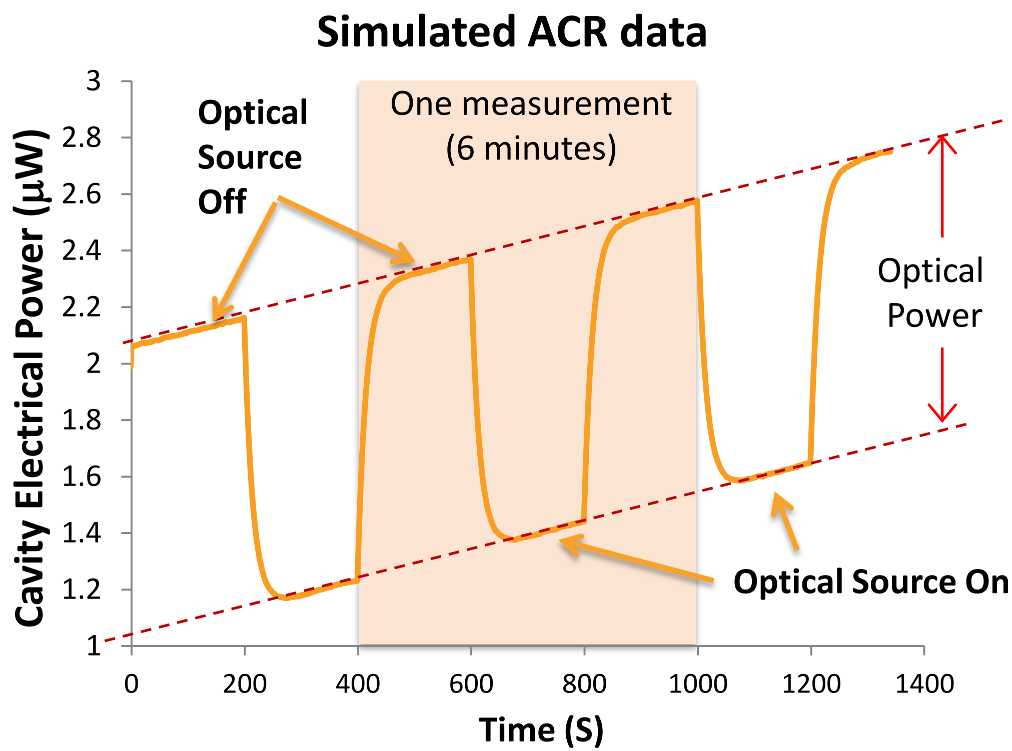
ACR Is Based Upon Principle of Electrical Substitution

- Heat sink & cavity actively stabilized
- Change of incident optical power equals change of cavity heater power
- Cavity heater power measured to 0.005% accuracy (typical)
- Only needs short term stability of thermal link & thermometry
- Insensitive to long term drifts



Typical Optical Power Measurement

- Cavity & heat sink controlled to constant temperature
- Cavity heater power biased higher than optical power
- Absolute temperature doesn't matter
- Data processing removes drift



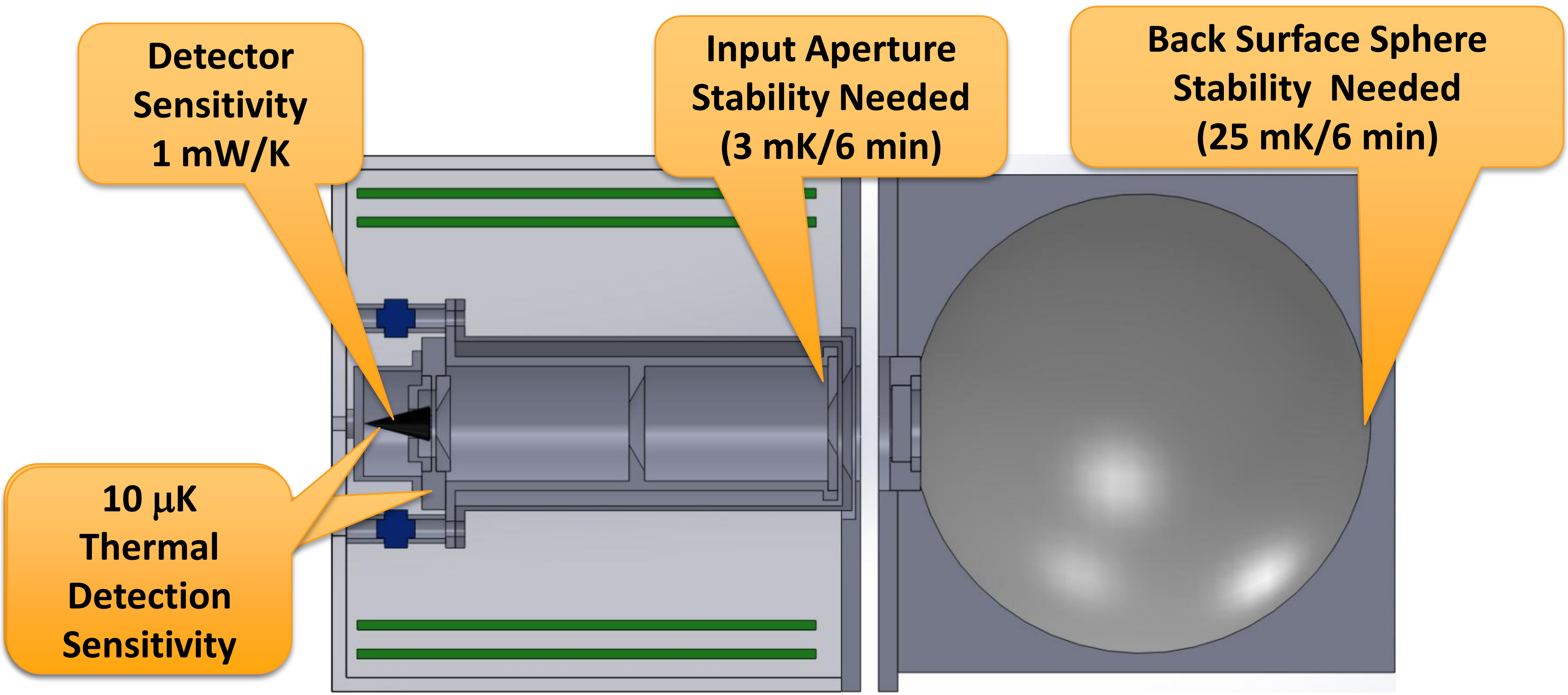
Phase 1 Study Improvements:

- Achieve temperature sensitivity & accuracy without use of superconductor temp sensors
- Achieve thermal control in much less stable environments
- Better electronics & smaller ACR for reduced mass & power
- Flexible ACR temperature set points

ACR Is Sensitive to All Wavelengths & Therefore Thermal Environment

Phase 1 study determined thermal environment needed to meet objectives

- Temperature control most of the scene viewed by ACR
- Run tight control loops for detector & heat sink
- Minimize environmental temperature fluctuations by good thermal engineering
- Electronics & sensors capable of resolving 10 μK temperature change



Active Cavity Radiometer (ACR) Is Ideal for Use as a Reference Standard in Space

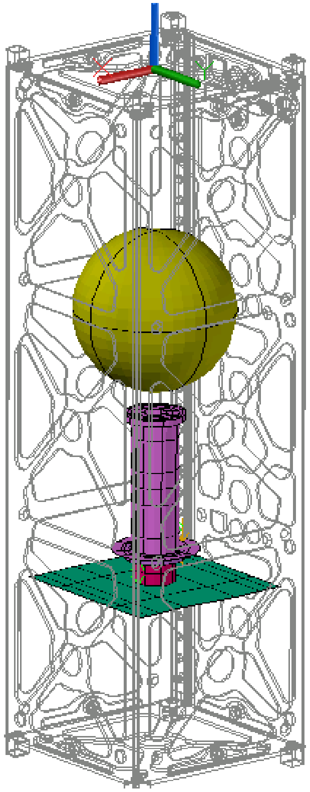
Specular Trap Black Body Detector

- Absorbs > 99.95% photons entering detector
- Photon energy converted to heat
- ~10 nW noise floor possible for a room temperature device
- Wavelength independent responsivity
- Detector insensitive to contamination or other degradation
- No ACR optics to degrade

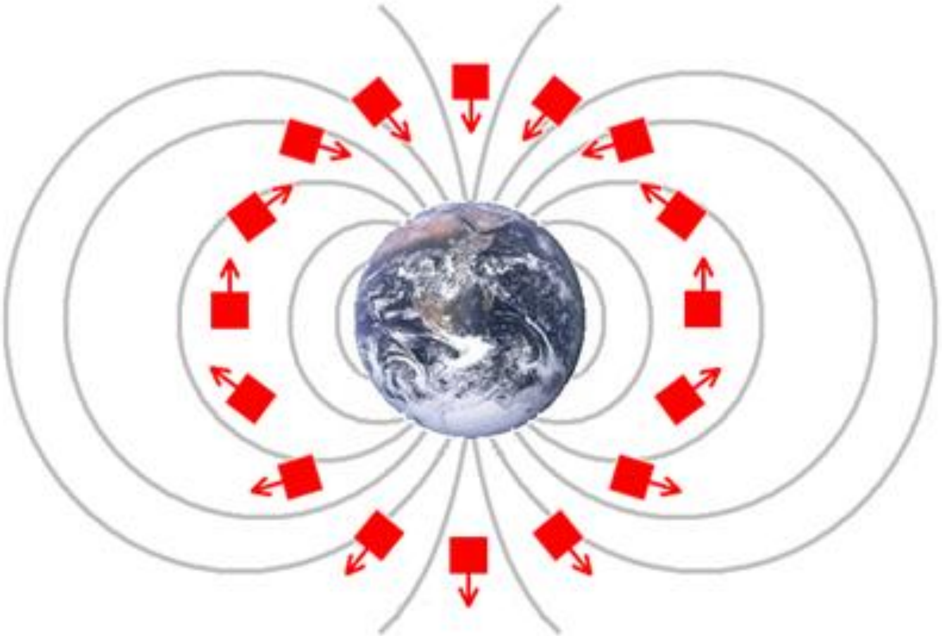
Our ACR used as an International Standard (SI) has no optical components nor does it have any electronic detectors that can degrade over time. Hence, its calibration accuracy is long lasting and suitable for decade long missions in space without significant change.

ACR & Sphere Thermal Simulations for 3U CubeSat Demonstration Were Conducted

3U CubeSat Configuration



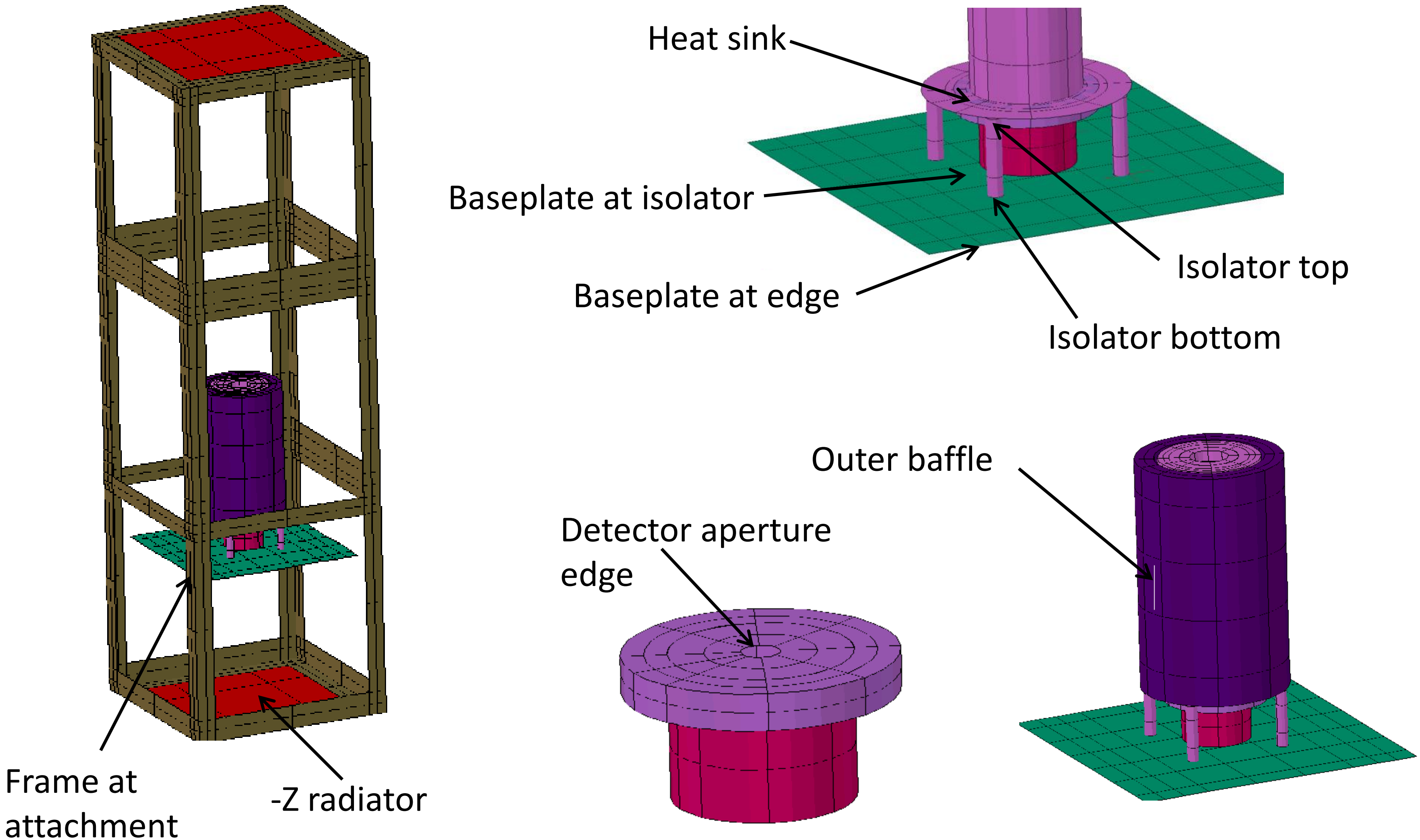
Passive magnetic orientation of CubeSat during an orbit



Two different sun-synchronous orbits simulated

- 800 km eclipse
- 800 km non-eclipse

Thermal Models Included
Various ACR Temperature Locations



Preliminary Results of On-orbit CubeSat Thermal Simulations Support Viability of Concept

- CubeSat cooling capacity adequate

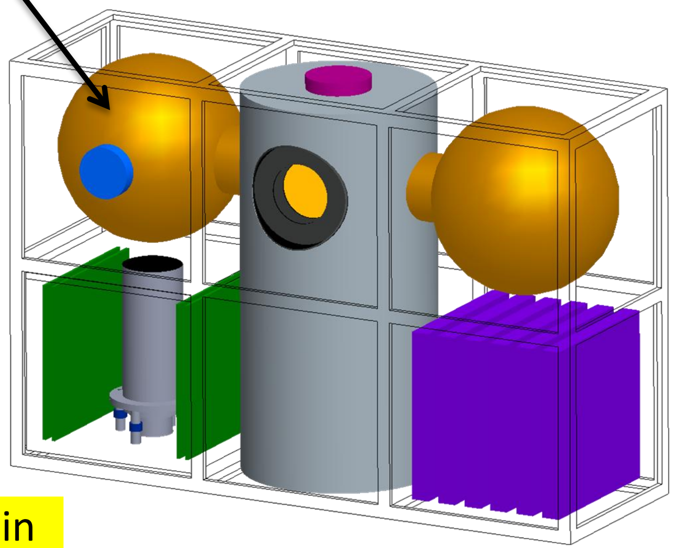
- Temperature gradients within ACR currently too high

- Design optimization expected to bring performance within bounds

- Programmable temperature set points desirable in ACR
  - Better accommodates all orbit types
  - Reduces cooling load
  - Optimizes performance for various optical loads

- Future simulations
  - LED sphere stability
  - Higher resolution sim (~100 μK)

LED Integrating Sphere Properties



Internal sphere coating

- BaSO$_4$
- 95% UV & VIS, > 90% in NIR

LED to sphere coupling

- UV/VIS fiber optic
- NIR fiber optic
- Thermally isolates LED from sphere

Integrating sphere

- Mechanical rotation in one axis 90 degree
- Thermal stability (back surface) 25 mK / 6 min
- Radiance uniformity (back surface) 0.1%

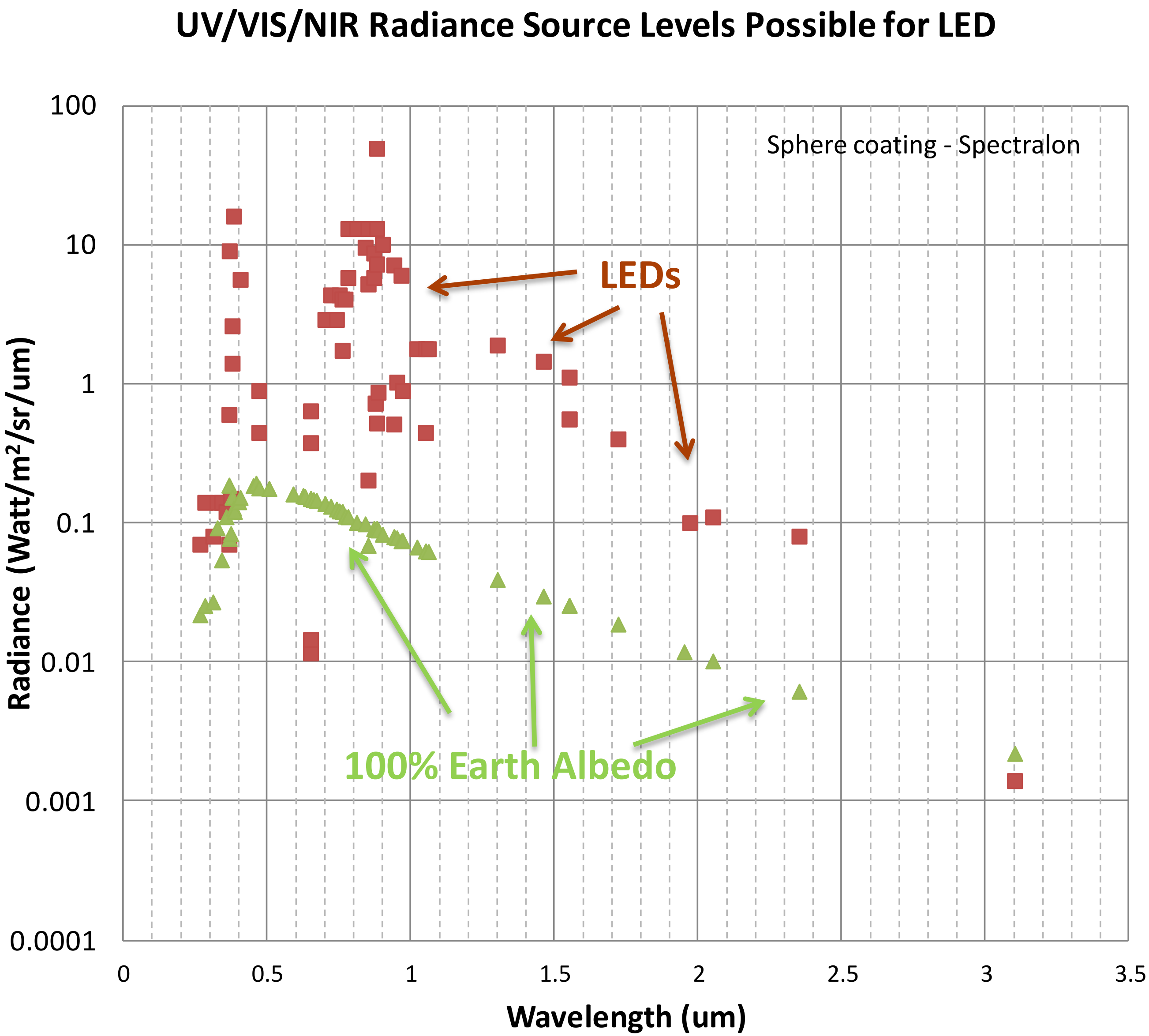
LED Sources

- Minimum of 15 discrete LED wavelengths spanning 250 nm – 3000 nm
- Commercially available, no fabricated optics (dyes only)

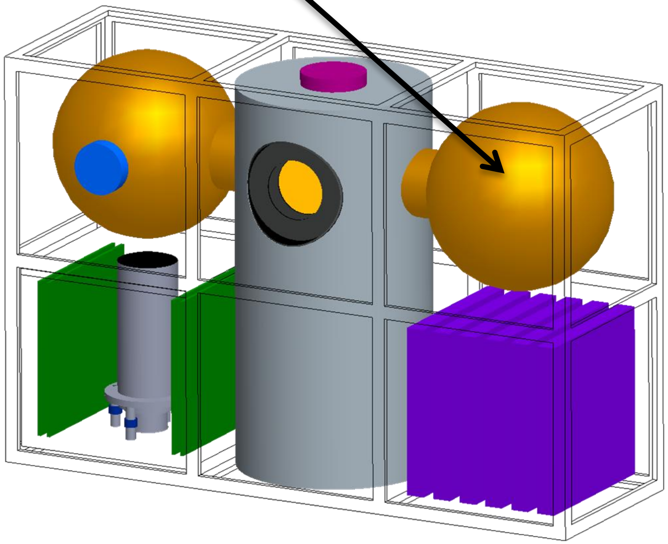
Short Term Radiance Stability

- 100 ppm
- Monitor detectors internal to sphere provide feedback
  - Si (200 nm – 1100 nm)
  - InAs (780 nm – 3000 nm)

Many LEDs Available to Calibrate Entire UV/VIS/NIR



White Light Integrating Sphere Properties



Internal sphere coating

> Spectralon
> 95% UV & VIS, > 90% in NIR

Source sphere coupling

> UV/VIS fiber optic
> NIR fiber optic
> Thermally isolates source from sphere

Integrating sphere

> Mounting fixed
> Thermal stability no requirement
> Radiance uniformity 2%

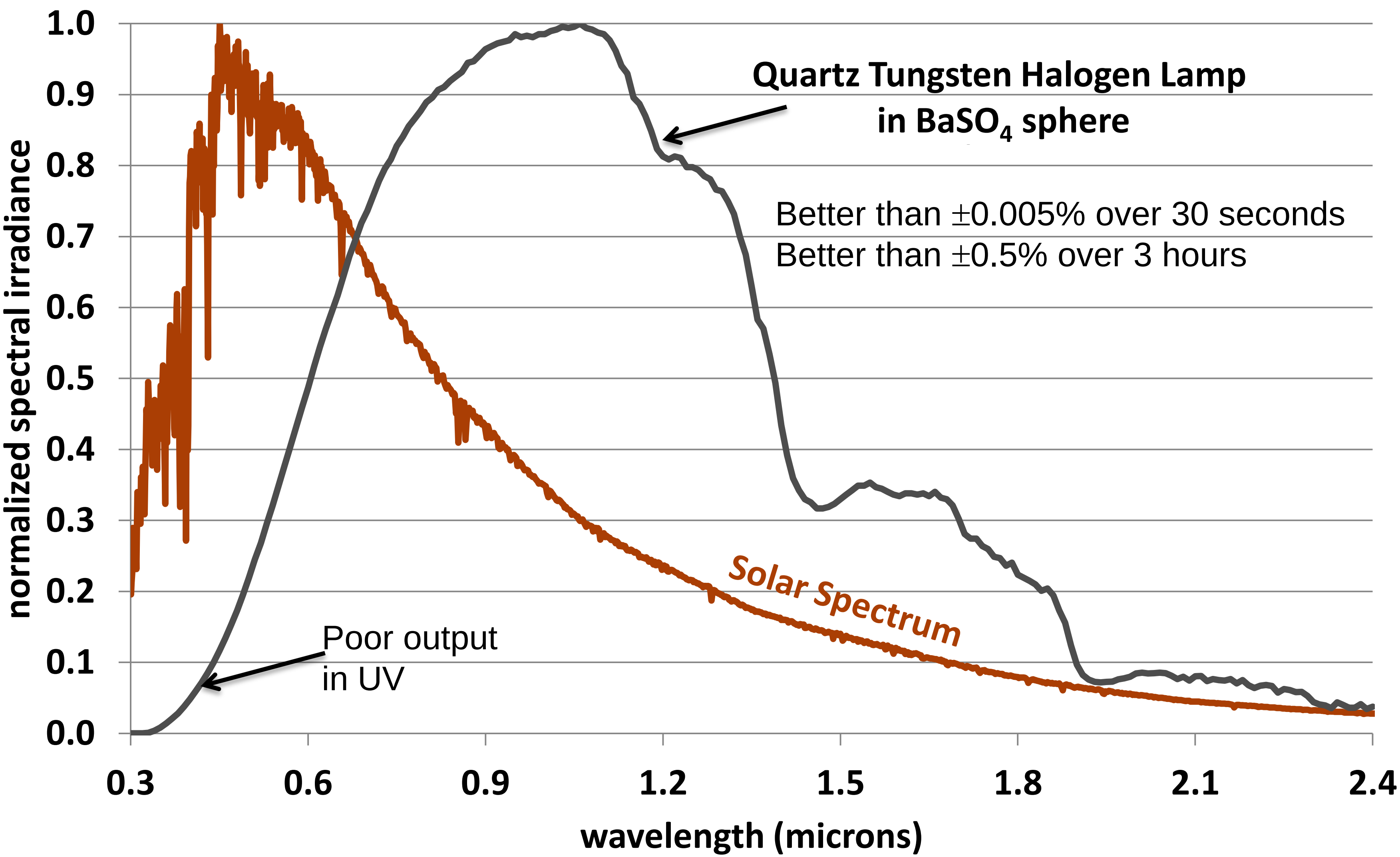
Sources

> (Option 1) Deuterium lamp & Quartz Tungsten Halogen lamp 200 nm – 3000 nm
> (Option 2) Laser driven plasma lamp

Short Term Radiance Stability Required

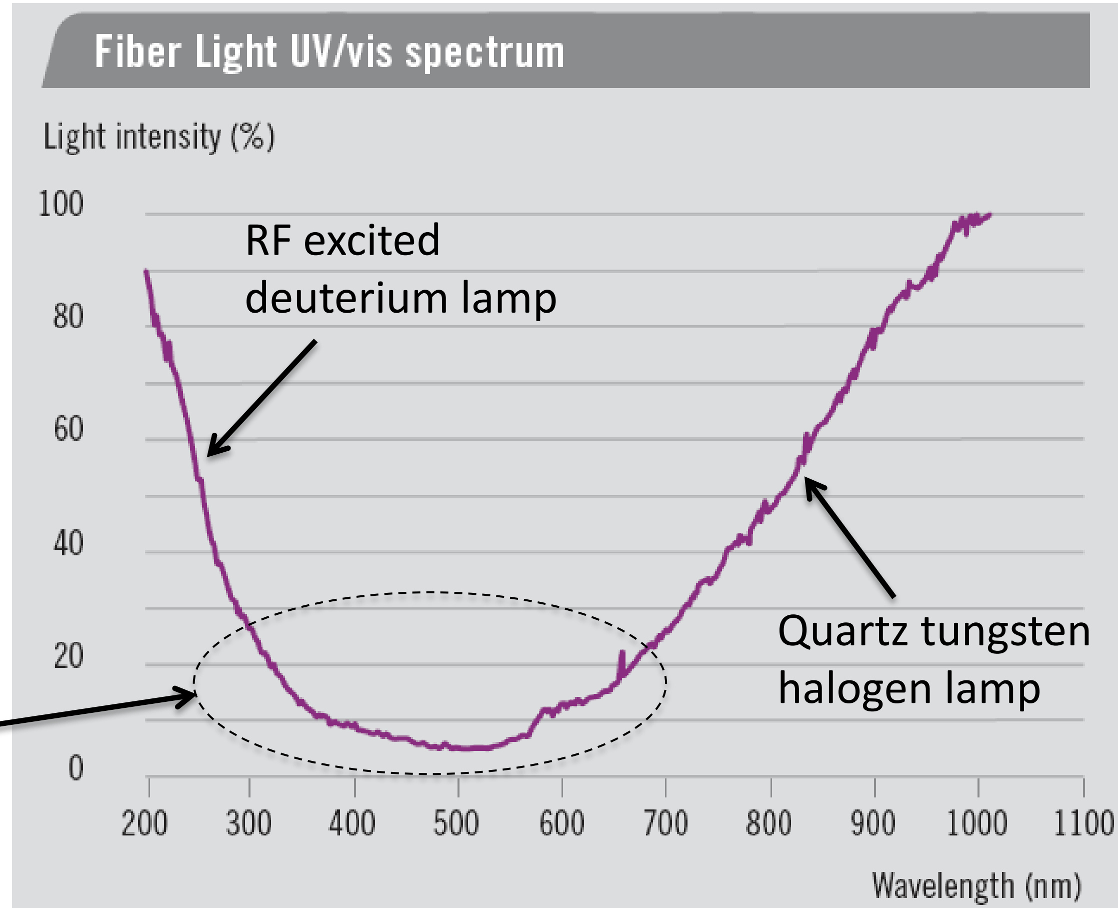
> 1000 ppm / 6 min

Quartz Tungsten Halogen Lamp Mismatched to Solar Spectrum …….But Very Stable for Calibration



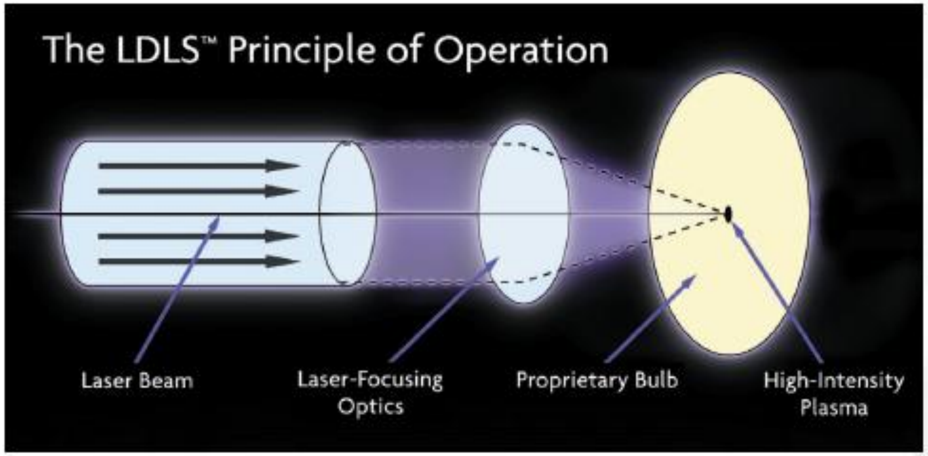
Combining Deuterium Lamp with Quartz Tungsten Halogen Lamp Fills in UV Spectrum

Commercial version with fiber optic

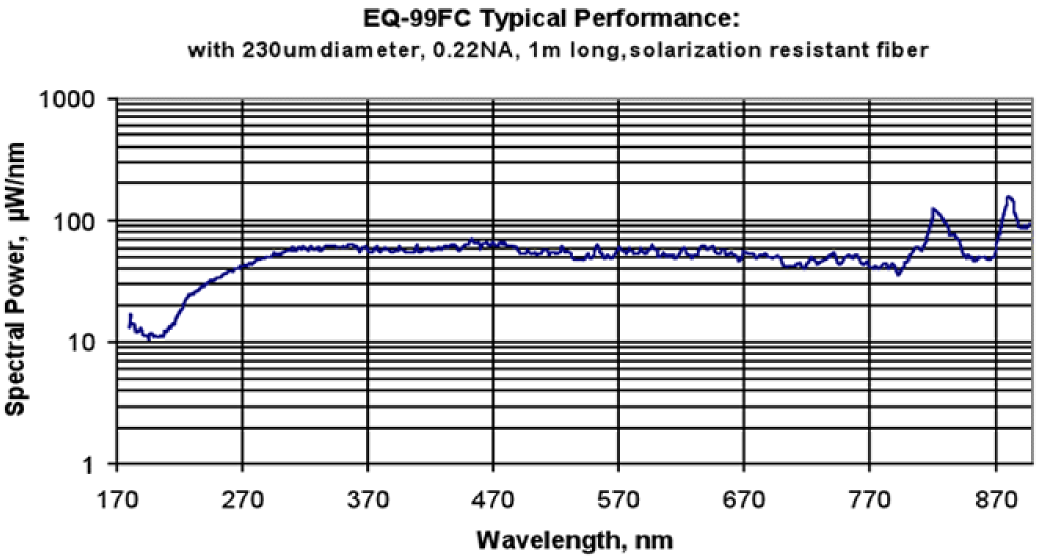


Lacks Uniformity Desired

Commercially Available Laser Driven Plasma Lamp Has Most Desirable UV/VIS Spectral Features



EQ-99FC lamp house with power supply

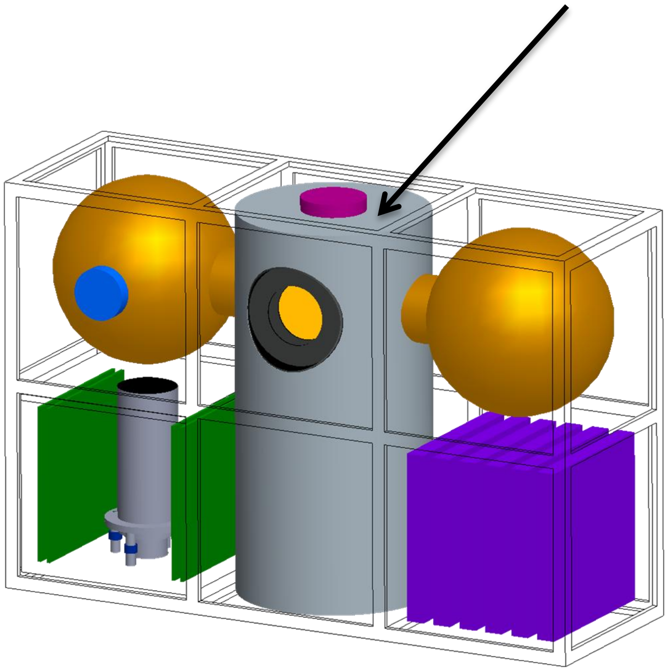


- Flat spectrum (200 – 800 nm)
- Output range (200 – 2100 nm)
- Calibration accuracy +/-5% (95% confidence) 1000 hours
- Order of magnitude longer life over deuterium bulbs

Essential Element of "NIST in Space" Is UV/VIS/NIR Fourier Transform Spectrometer (FTS)

FTS Approach

- One detector produces entire spectrum for an octave or more
- Do not need to calibrate every spectral channel
- Total power in spectral band can be concentrated into one LED wavelength without saturating instrument
- Lower ACR sensitivity needed



Grating Spectrometer Approach

- Needs every detector to be separately calibrated (Too many LEDs)
- Needs a significantly more sensitive ACR
- ACR must be cryogenically cooled

Grating Spectrometer NOT Compatible with "NIST in Space" Concept

UV/VIS/NIR Fourier Transform Spectrometer (FTS)

Interferometer

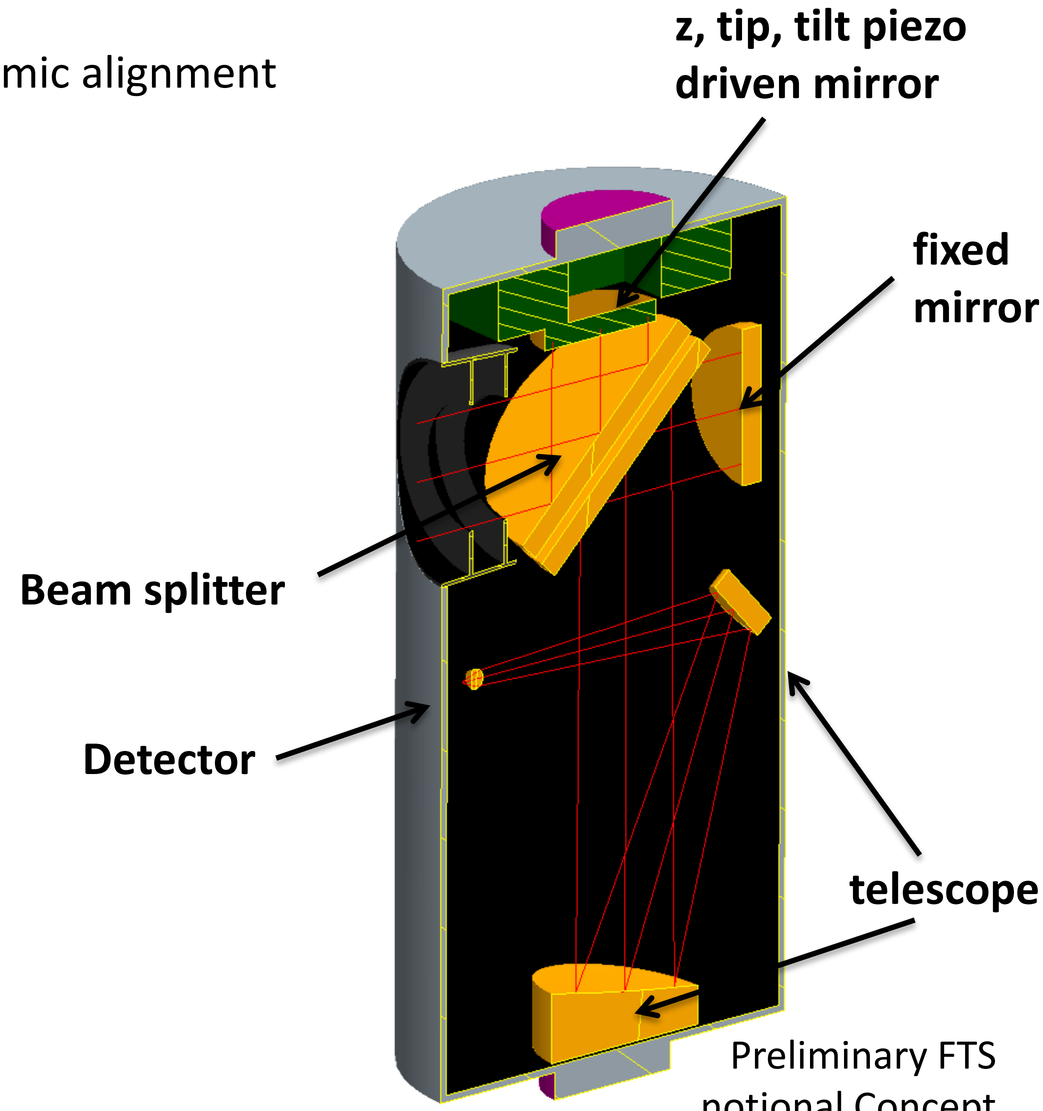
- Plane mirror Michelson with dynamic alignment
- Beam splitter 200 nm – 3000 nm
- FOV size 1^{o}
- Resolution 1.4 cm^{-1}
- Mechanism z, tip, tilt piezo
- Sweep rate 0.1 cm/sec

Metrology

- Laser diode 1550 nm
- Sampling 38.75 nm
- Interpolation 20x

Detectors

- GaP 200 – 555 nm
- Si 400 – 1100 nm
- InAs 780 – 3000 nm



Preliminary FTS notional Concept

Phase 1 Study Accomplishments

- Showed 0.1% ACR calibration can be achieve without cryogenic cooling
- Showed calibration can be achieved at 100% earth albedo radiance levels
- Components available for sources: LEDs, fiber optics, lamps, and interfaces
- Thermal background stability & background cancellation methods make the broadband ACR effective as a UV/VIS/NIR radiance meter while using an <u>un-cooled</u> visible source
- Combined above properties into a well defined UV/VIS/NIR hyperspectral system concept backed by analysis & achievable subsystem requirements

We believe we have advanced the NIST in Space concept from TRL2 to TRL3.

Subsequent Phase 2 NIAC research would focus on prototype builds, experimental verification and UV/VIS/NIR FTS definition